Spatial superpositions as a resource for quantum information processing

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One of the most basic principles that differentiate quantum and classical theory is the superposition principle (SP). When applied to composite systems, this principle leads to quantum entanglement, which played over the years a pivotal role both in quantum foundations (via Bell's theorem [Bell64]) and quantum information (prominently via quantum computing). However, since the theory itself does not impose fundamental limitations to the SP, the latter can be applied to a variety of degrees of freedom, leading to various non-classical phenomena, ranging from the historical Schrödinger's cat paradox [Sch35] to more recent proposals on superpositions of orders [OBC12], gates and channels [CK19], communication directions [DSD18], etc. These studies on the SP opened entirely new directions in the field of quantum information and quantum foundations. Given the fact that conventional methods of quantum information processing (e.g. circuit model or measurement-based quantum computing) are maturing into quantum technologies and real-world applications, there is a need for novel theoretical models that go beyond the standard paradigm. In this respect, recent studies on novel applications of the SP have been very promising and there is a great community interest in pursuing this research direction. There are two principal aspects I would like to address here:

Multi-way signaling with a single quantum particle. In classical physics, information carriers are well-located in space at every instant of time. For example, in communication protocols, an information carrier (such as a short light pulse) has well defined space-time coordinates while carrying the information from the sender to the receiver. In contrast, a quantum information carrier in spatial superposition does not share this property, which in turn enables for novel possibilities of information transmission. For example, if the carrier is “simultaneously located” at two locations A and B via spatial superposition and consequently is exchanged between A and B, one can achieve two-way communication using only a single quantum particle, as it has been demonstrated in [DSD18, DSD20]. This simple protocol demonstrates the power brought forth by spatial superposition: it enables a bidirectional flow of information with A and B being senders and receivers of the information at the same time—a task prohibited by the laws of classical physics. The generalizations to multi-way-signaling have been proposed in [HS19].

Quantum enhancement to information speed. Usually, when one talks about information speed, one envisions two parties A (sender) and B (receiver); A sends a message encoded in a physical system (information carrier) to B and the information speed is simply the speed of the signal which is limited by the speed of light. In this sense, quantum mechanics cannot provide any enhancement to the information speed. However, what if the information that needs to be transmitted is not localized at the single (sender's) station? What if the information of interest is encoded in a global property of dispersed pieces of information, each localized at a different location? In this respect, the protocol of [DSD18] (see previous paragraph) can be seen in light of enhancement to the speed of the transmission of information, as a quantum carrier completes the tasks twice faster than the classical one. We generalized this protocol to the multipartite scenario in [HS19, HS20], where the goal was to collect and transmit a global property of N dispersed pieces of information, each localized at a different location. Surprisingly, we have shown that spatial superposition provides an arbitrarily large effective enhancement to the speed of collecting and transmitting the (global) information for any N.

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